PATENT

Process for countering the vibrations induced in an aircraft by the windmilling of a fan and system of electric flight controls implementing this process.

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The present invention relates to a process making it possible to counter the vibrations induced, in an aircraft equipped with turbofans, by the windmilling of at least one of the fans of said turbofans. It also relates to a system of electric flight controls for aircraft implementing this process.

It is known that, when an aircraft turbofan is shut down in flight, for example following the rupture of one or more blades of its fan, the latter revolves in free rotation or autorotation under the effect of the airstream entering said turbofan. This phenomenon is designated in aeronautics, in a general manner, by the term "windmilling".

Such windmilling of a fan induces and propagates vibrations in the aircraft, their frequency depending on the phase of flight, but lying between 5 and 15 Hz. Such induced vibrations, on the one hand, subject the structure of the aircraft, and hence the crew and the passengers, to considerable vibratory loads and, on the other hand, may make the piloting tasks difficult, or even impossible, for the pilot who is subjected thereto.

To be able to resist these vibratory loads, the structure of the aircraft, the furnishings, the supports, the computers, the seats, etc have to be reinforced accordingly, thereby raising the total weight of the aircraft. When the aircraft is of large dimensions and is equipped with powerful engines, the reinforcements required to resist the induced vibrations give rise to an appreciable increase in weight of the aircraft, thereby impairing the latter's performance. Moreover, considerable reinforcements such as these relate only to the mechanical strength of the structure of the aircraft and do not in any way

ameliorate the difficulties of piloting and the discomfort of the passengers and of the crew.

The object of the present invention is to remedy these drawbacks by avoiding an exaggerated increase in the weight of the aircraft, while allowing the pilot of the aircraft always to be able to perform the piloting tasks easily.

For this purpose, according to the invention, a process making it possible to counter the vibrations induced, in an aircraft equipped with engines of the turbofan type, by the windmilling of at least one of the fans of said engines, said aircraft comprising a system of electric flight controls which:

- produces electric flight control commands intended for servocontrols able to actuate the control surfaces of said aircraft; and
- slaves said servocontrols to said electric flight control commands, limiting the operation of said servocontrols in a reduced frequency band, usually of the order of from 0 to 4 Hz,

is noteworthy:

- in that the appearance of said induced vibrations is monitored; and
- in that in case of detection of such induced vibrations:
  - an additional electric control command is computed, which, applied to the servocontrol of at least one control surface, allows the latter to oppose said induced vibrations;
  - the electric flight control command relating to said control surface and said additional electric control command are summed to obtain an overall control command for said control surface; and
  - said servocontrol is temporarily slaved to said overall control command, allowing the operation

of said servocontrol in a widened frequency band, of the order of 0 to 15 Hz.

Thus, according to the invention, there is active intervention against the vibrations induced by the windmilling of a fan, rather than just passive intervention, as was done hitherto by reinforcing the structure of the aircraft. As a result, the structural reinforcements may be less considerable (thereby allowing significant savings of weight) and the piloting and comfort conditions are improved.

It is known that the state of the art, as regards the servocontrols used on board aircraft, consists in operating said servocontrols in a frequency passband limited above to 3 or 4 Hz, in particular out of fatigue and lifetime considerations, this passband being compatible with the frequencies controlled by the pilots or by the automatic pilot.

Now, as already mentioned above, the vibrations induced by the windmilling of at least one fan are higher and lie between 5 and 15 Hz.

It is therefore impossible for the vibratory motions produced by windmilling to be controlled by the control surfaces of the aircraft.

However, if the standard servocontrols are examined, it is noted that their actuating ram may operate at frequencies of at least 15 Hz and that the constraining of said servocontrols to a reduced frequency band is carried out in the slaving loops, which control them and which are installed in a flight control computer, by filtering of the control commands and by fixing to low values of their slaving gain.

Hence, in accordance with the present invention, when the phenomenon of windmilling is detected, the command (the additional electric control command) that must be addressed to the servocontrol of a control surface in order for the latter to counter the vibratory effects of this phenomenon is computed and said servocontrol is temporarily unconstrained so that it can operate exceptionally and temporarily at frequencies above these standard operating frequencies and thus obey said additional command.

It will be noted that, when windmilling of a fan occurs on board an aircraft, the objective of the pilot is to land as quickly as possible, so as to be able to repair or change the shut-down engine, before any resumption of flight. Thus, the aircraft, in which the windmilling will have been countered in accordance with the present invention, will only occasionally fly under widened unconstrained slaving, so that the impact on the fatigue of the servocontrols will be negligible.

It will be noted moreover that the additional electric command charged with countering said induced vibrations is not substituted for the flight control command, but is added to the latter by being juxtaposed thereto, since their frequency domains (5-15 Hz for one and 0-3 Hz for the other) are different. Thus, the piloting of the aircraft is not modified by the implementation of the process in accordance with the present invention.

Advantageously, the detection of said induced vibrations is obtained through accelerometric measurements at at least one point of the aircraft. Preferably, each of these points neighbors an engine, since it is the fan of one of them that might be the source of said vibrations. In these accelerometric measurements, those whose frequency lies between 5 Hz

and 15 Hz (frequency span characteristic of windmilling) are examined and their amplitude is compared with a predetermined threshold, representative of said induced vibrations. Such a threshold is preferably determined on the basis of the modified aeroelastic model specific to said aircraft and to said engines, as is explained hereinbelow.

Moreover, to compute said additional electric control command, accelerometric measurements representative of said induced vibrations are performed at at least one location of said aircraft, and said additional electric control command is determined on the basis of preestablished relations at which, for each acceleration of said location, are able to deliver one such additional electric control command.

Advantageously, these preestablished relations also emanate from said modified aeroelastic model.

It is known that the aeroelastic model specific to an aircraft indicates, among other information, on the one hand, the amplitude, the frequency and the phase of the vibrations produced in the fuselage of the aircraft as a function of the accelerations undergone by the latter at the level of each engine and, on the other hand, the amplitude, the frequency and the phases of the vibrations produced in the fuselage of the aircraft by the toings and froings of each control surface. An aeroelastic model such as this is usually computed theoretically by the aircraft's manufacturer.

Moreover, the manufacturer of an aircraft turbofan determines, in a standard fashion, by computation, the windmilling model for the fan of said turbofan, indicating the amplitude, the frequency and the phase of the vibrations produced in the aircraft, at the location of said turbofan, by such windmilling.

Thus, by combining these two models, a modified aeroelastic model is obtained that makes it possible to establish said relations determining the order that must be addressed to a control surface so as to counter the vibrations produced at a location of the aircraft by the windmilling of an engine fan.

Of course, this modified aeroelastic model is purely theoretical and, if necessary, it is advantageous to supplement it and/or to improve it experimentally, for example through in-flight trials.

From the foregoing, it will be readily understood that said modified aeroelastic model also makes it possible to determine said amplitude threshold, serving to detect the appearance of said induced vibrations.

In one practical form of implementation of the process according to the invention, relating to an aircraft comprising at least two pairs of symmetric control surfaces (ailerons, flaps, elevators, etc), steered by a vertical flight control command and by a lateral flight control command (that is to say horizontal and orthogonal to the longitudinal axis of said aircraft):

- a first additional electric control command able to counter the vertical component of said induced vibrations at said location is computed;
- a second additional electric control command able to counter the lateral component of said induced vibrations at said location is computed;
- said electric vertical flight control command and said first additional electric control command are summed to obtain a first overall control command;
- said lateral flight control command and said second additional electric control command are summed to obtain a second overall control command;

- the servocontrols of the two symmetric control surfaces of one of said pairs are slaved to said first overall control command, in common, in such a way that these control surfaces deflect symmetrically in the same direction; and
- the servocontrols of the two symmetric control surfaces of the other of said pairs are slaved to said second overall control command, in common, in such a way that these latter control surfaces deflect antisymmetrically in opposite directions.

The present invention relates moreover to a system of electric flight controls implementing the process described hereinabove.

For this purpose, according to the invention, a system of electric flight controls for an aircraft, which is equipped with engines of the turbofan type, each comprising a fan able to windmill in case of shutdown of said engine in flight, said system producing, for the control surfaces of said aircraft, electric control commands which are addressed to respective servocontrols able to actuate said control surfaces by way of slaving means limiting the operation of said servocontrols in a reduced frequency band, usually of the order of 0 to 4 Hz, is noteworthy in that it comprises:

- means of detection of the appearance of the vibrations induced in the aircraft by the windmilling of at least one of said fans;
- means of measurement of said induced vibrations at at least one location of said aircraft;
- at least one table in which are recorded preestablished relations between the vibrations induced at said location and the order that must be addressed to at least one control surface to counter said induced vibrations;

- means of computation, connected to said means of measurement and to said table, to produce an additional electric control command which, applied to at least said control surface, is able to counter said vibrations induced at least at said location of said aircraft;
- means of summation making it possible to combine, into an overall control command for said control surface, said electric control command which relates thereto and said additional electric control command; and
- means for temporarily slaving said servocontrol to said overall command, allowing the operation of said servocontrol in a widened frequency band in the order of 0 to 15 Hz.

Said means of detection and said means of measurement comprise accelerometers. If necessary, these accelerometers could be common to both these means. However, preferably, for reasons of efficiency, each of said means comprises its own accelerometers, those of the means of detection being disposed in the neighborhood of said engines which are the source of said induced vibrations and those of the means of measurement (which determine the parameters of the action to be undertaken against said induced vibrations) being disposed rather in the fuselage and on the flight deck, precisely where the effect of said induced vibrations has to be combated most for the comfort of the passengers and the steerability of the aircraft.

The means of slaving to a reduced frequency band and the means of temporary slaving to a widened frequency band may consist of distinct slaving devices. In this case, said system of electric flight controls comprises means of switching making it possible, when said means

of detection detect the appearance of said induced vibrations, to:

- disable the device for slaving to a reduced frequency band; and
- enable said device for temporary slaving to a widened frequency band in such a way that the servocontrol associated with said control surface can be governed by said overall control command.

As a variant, said means of slaving to a reduced frequency band and means of temporary slaving to a widened frequency band consist, at least in part, of the same hardware items, at least some of which (in particular the gain amplifiers) are adjustable so as to allow the frequency operating limit to be shifted from at most 4 Hz to at least 15 Hz.

Preferably, said means of computation are disabled while no windmilling of a fan is detected and they are enabled by said means of detection upon the appearance of said induced vibrations.

In the general case where the aircraft comprises at least two pairs of symmetric control surfaces and where said system of electric flight controls produces for said control surfaces a electric vertical flight control command and a electric lateral flight control command:

- said means of measurement deliver the vertical component and the lateral component of said induced vibrations;
- said means of computation compute a first and a second additional electric control command able respectively to counter said vertical and lateral components of said induced vibrations;
- said means of summation add together:

- said vertical electric flight control command and said first additional electric control command to form a first overall control command;
- said lateral electric flight control command and said second additional control command to form a second overall control command; and

- said means of temporary slaving to widened frequency band slave, to said first overall control command, the servocontrols of the two symmetric control surfaces of one of said pairs, in such a way that these latter control surfaces deflect symmetrically in the same direction; and
- said means of temporary slaving to widened frequency band slave, to said second overall control command, the servocontrols of the two symmetric control surfaces of the other of said pairs in such a way that these latter control surfaces deflect antisymmetrically in opposite directions.

Preferably, said means of computation and said table form an integral part of said system of electric flight controls.

The figures of the appended drawing will elucidate the manner in which the invention may be embodied. In these figures, identical references designate similar elements.

Figure 1 shows, in perspective from above, a wide-bodied airplane.

Figure 2 shows the schematic diagram of a system of electric flight controls for the airplane of figure 1, said system being enhanced in accordance with the present invention so as to avoid the vibratory effects of the windmilling of the fan of at least one engine of said airplane.

Figure 3 illustrates a variant embodiment of the system of figure 2.

The four-engined wide-bodied airplane 1, represented diagrammatically in perspective in figure 1, comprises a fuselage 2 of longitudinal axis L-L and two wings 3 and 4 disposed on either side of said fuselage 2. Each wing carries an inboard engine 5 or 6 and an outboard engine 7 or 8, said engines 5 to 8 being of the turbofan type. Moreover, among other control surfaces, the wing 3 carries an inboard aileron 9 and an outboard aileron 10. Likewise, the wing 4 carries, among other control surfaces, an inboard aileron 11 and an outboard aileron 12. The two wings 3 and 4 are mutually symmetric with respect to the fuselage 2 as are their engines and their ailerons, taken pairwise. At the rear, the airplane 1 moreover comprises symmetric horizontal empennages 13 and 14, respectively provided with mutually symmetric elevators, bearing the references 15 and 16 respectively.

To control one or the other of the control surfaces 9 to 12, 15 and 16, the airplane 1 comprises a system of electric flight controls 17, receiving steering commands for steering members 18 and 19 (stick, rudder bar, etc) actuated by a pilot or through an automatic pilot 20, as is represented in figure 2. In response to said steering commands, said system of electric flight controls 17 computes a vertical electric flight control command dZ and a lateral electric flight control command (that is to say horizontal and orthogonal to the axis L-L) dY.

Represented in figure 2 are two pairs of symmetric control surfaces 21A, 21B on the one hand, and 22A, 22B on the other hand.

The pair of control surfaces 21A, 21B is representative of one or the other of the pairs of symmetric control surfaces 9-11, 10-12 and 15-16 described hereinabove. Preferably, the pair of control surfaces 22A-22B is representative of one or the other of the pairs of symmetric control surfaces 9-11 and 10-12.

Each control surface 21A, 21B, 22A, 22B is provided with a respective rotation shaft 23A, 23B, 24A, 24B, about which it can revolve under the action of a respective servocontrol 25A, 25B, 26A, 26B.

The servocontrols 25A and 25B are controlled in common by a slaving device 27A receiving said vertical command dZ from the system 17 and they deflect the two control surfaces 21A and 21B symmetrically, in the same direction.

The servocontrols 26A and 26B are controlled in common by a slaving device 28A receiving said lateral command dY from the system 17 and may deflect the two control surfaces 22A and 22B antisymmetrically, in opposite directions.

In standard fashion, in order to limit the fatigue of the servocontrols 25A, 25B, 26A, 26B and to reduce their sensitivity to noise, the slaving devices 27A and 28A - which may be of the open loop type or on the contrary of the closed loop type with positional feedback of the corresponding control surfaces - deliberately limit, by virtue of filters and of reduced slaving gains, the operation of said servocontrols to frequencies at most equal to 4 Hz. The frequency band from 0 to 4 Hz in which said servocontrols are permitted to operate is defined by the frequency filtering of the commands dZ and dY in said slaving devices 27A and 28A, as well as by the choice of a low slaving gain for them.

Moreover, on the nacelles of the engines 5 to 8 or at other places neighboring them, are mounted accelerometers 29 to 32 measuring the vertical and lateral components of the oscillatory accelerations to which they are subjected. The accelerometers 29 to 32 transmit their accelerometric measurements to a detector 33, able to detect windmilling of the fan of at least one of the engines 5 to 8. To do this, the detector 33 searches through the accelerometric measurements that are addressed to it for the accelerations whose frequency lies between 5 Hz and 15 Hz (frequencies characteristic of windmilling) and whose amplitude is above a threshold, which is determined by computation (as indicated hereinabove with regard to the modified aeroelastic model) and/or by trials and which is representative of the appearance of the windmilling of at least one of the fans.

Likewise, at diverse locations of the wide-bodied airplane 1, in particular in the passenger cabin and on the flight deck, are mounted accelerometers 34.1 to 34.n, etc measuring, at these locations, the vertical and lateral components of the oscillatory accelerations. These latter measurements are addressed to a computer 35A, able to compute additional electric control commands δZ and δY which, applied respectively to the servocontrols 25A, 25B of the control surfaces 21A, 21B and to the servocontrols 26A, 26B of the control surfaces 22A, 22B, allow these control surfaces to counteract the vibrations at the locations of the accelerometers 34.1 to 34.n.

A table 35B is incorporated into the computer 35A and it contains relations which are preestablished on the basis of said modified aeroelastic model, such as defined hereinabove, and which, for each vertical and lateral component of the accelerometric measurements at

the locations of the accelerometers 34.1 to 34.n, deliver additional electric control commands δZ and δY able to counter respectively said components at these locations and appearing at the two outputs of the computer 35A.

In parallel with the slaving devices 27A and 28A are, moreover, respectively mounted additional slaving devices 27B and 28B - of the open loop type or of the closed loop type - allowing the servocontrols 25A, 25B, 26A and 26B to operate at frequencies at least equal to 15 Hz.

In a similar manner to what was mentioned in respect of the slaving devices 27A and 28A, the widened frequency band of 0 to 15 Hz in which the slaving devices 27B and 28B permit the operation of the servocontrols 25A, 25B, 26A, 26B is defined by frequency filters incorporated into said devices 27B and 28B, as well as by the choice of a higher slaving gain for them.

The inputs of the slaving devices 27A and 27B are connected to the output of a summator 36, an input of which is connected to the output dZ of the system of electric flight controls 17 and the other input of which can be connected to the output δZ of the computer 35A, by way of a switch 37, controlled by the detector 33. Moreover, one or the other of the outputs of the slaving devices 27A and 27B is connected to the servocontrols 25A and 25B by a switch 38, likewise controlled by the detector 33.

In a similar manner, the inputs of the slaving devices 28A and 28B are connected to the output of a summator 39, an input of which is connected to the output dY of the system of electric flight controls 17 and the other input of which can be connected to the output δY of the computer 35A, by way of a switch 40,

controlled by the detector 33. Moreover, one or the other of the outputs of the slaving devices 28A and 28B is connected to the servocontrols 26A and 26B by a switch 41, likewise controlled by the detector 33.

When the detector 33 detects no acceleration whose frequency lies between 5 Hz and 15 Hz and whose amplitude is above said predetermined threshold, the switches 37 and 40 disable the computer 35A and the switches 38 and 41 connect the output of the slaving device 27A to the servocontrols 25A and 25B and the output of the slaving device 28A to the servocontrols 26A and 26B.

Thus, when, in flight, none of the engines 5 to 8 is shut down, the servocontrols 25A, 25B, 26A and 26B (and hence the control surfaces 21A, 21B, 22A, 22B) are respectively controlled by the system of electric flight controls 17 alone, by way of the summators 36 and 39 and of the devices for slaving 27A and 28A to operating frequency band limited above to 4 Hz.

On the other hand, as soon as the detector 33 detects induced vibrations, due to the windmilling of the fan of at least one shut-down engine 5 to 8, it toggles the switches 37, 38, 40 and 41. Thereby, the computer 35A and the devices for slaving 27B and 28B to widened frequency band are enabled, whereas the slaving devices 27A and 28A are disabled. In this case, the servocontrols 25A, 25B and 26A, 26B are respectively controlled by overall commands represented by the sums $dZ + \delta Z$ and $dY + \delta Y$ of the control commands dZ, dY produced by the system 17 and the additional control commands δZ and δY computed by the computer 35A, said sums being calculated respectively by the summators 36 and 39 and being applied by way of the devices for slaving 27B and 28B to widened frequency band.

The control surfaces 21A and 21B may therefore oscillate symmetrically, under the dependence of the additional control command δZ, so as to counter the vertical components of the vibrations induced by the windmilling of the fan of at least one of the engines 5 to 8, while responding to the control command dZ produced by the system of flight controls 17.

Likewise, the control surfaces 22A and 22B can oscillate antisymmetrically, under the dependence of the additional control command δY, so as to counter the lateral components of the vibrations induced by such windmilling, while responding to the control command dY emanating from the system 17.

In the variant embodiment of figure 3, all the elements shown in figure 2 are found again, with the exception of the switches 38 and 41, which have been removed. Moreover, the slaving devices 27A and 27B have been removed and replaced with a single slaving device 42. Likewise, the slaving devices 28A and 28B have been removed and replaced with a single slaving device 43.

These slaving devices 42 and 43, which may be of the open loop type or of the closed loop type, comprise adjustable elements, for example slaving gain amplifiers, controlled by the detector 33. Thus, in the absence of windmilling of at least one of the fans, the slaving devices 42 and 43 limit the operation of the servocontrols 25A, 25B, 26A, 26B to the reduced frequency band of 0 to 4 Hz. On the other hand, in case of appearance of windmilling, the adjustable elements of the slaving devices 42 and 43 are controlled by the detector 33 to allow the operation of said servocontrols 25A, 25B, 26A, 26B at the widened frequency band of 0 to 15 Hz.